

# Search for Pair Production of Scalar Top Quarks in $R$ -parity Violating Decay Modes in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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## Abstract

We present the results of a search for pair production of scalar top quarks ( $\tilde{t}_1$ ) in an  $R$ -parity violating supersymmetry scenario in  $106 \text{ pb}^{-1}$  of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8 \text{ TeV}$  collected by the Collider Detector at Fermilab. In this mode each  $\tilde{t}_1$  decays into a  $\tau$  lepton and a  $b$  quark. We search for events with two  $\tau$ 's, one decaying leptonically ( $e$  or  $\mu$ ) and one decaying hadronically, and two jets. No candidate events pass our final selection criteria. We set a 95% confidence level lower limit on the  $\tilde{t}_1$  mass at  $122 \text{ GeV}/c^2$  for  $\text{Br}(\tilde{t}_1 \rightarrow \tau b) = 1$ .

Many supersymmetry (SUSY) models [1] predict that the first two generations of supersymmetric partners of the quarks and the leptons (squarks and sleptons) are approximately mass degenerate. However, the mass of the lightest top squark ( $\tilde{t}_1$  or ‘stop’) can be relatively light due to a large mixing between the interaction eigenstates,  $\tilde{t}_L$  and  $\tilde{t}_R$ . This mixing depends in part on the top Yukawa coupling which is largely due to the heavy top quark mass, and it is possible that  $\tilde{t}_1$  is lighter than the top quark [2].

$R$ -parity ( $R_p$ ) is a multiplicative quantum number defined as  $R_p \equiv (-1)^{3B+L+2S}$ , where  $S$ ,  $B$  and  $L$  are the spin, baryon and lepton numbers of a particle, respectively [3].  $R_p$  distinguishes SM particles ( $R_p = +1$ ) from SUSY particles ( $R_p = -1$ ). Conservation of  $R_p$  requires SUSY particles to be produced in pairs and to decay, through a cascade, to SM particles plus the stable lightest supersymmetric particle. The  $R_p$  conservation, which is not required by SUSY, is often built into the theory by hand and is justified phenomenologically by limits on the proton lifetime, the absence of flavor-changing neutral currents, etc. Viable  $R_p$  violating ( $\mathcal{R}_p$ ) models can be built by adding explicit  $\mathcal{R}_p$  terms with trilinear couplings ( $\lambda_{ijk}$ ,  $\lambda'_{ijk}$ ,  $\lambda''_{ijk}$ ) and spontaneous  $\mathcal{R}_p$  terms with bilinear couplings ( $\epsilon_i$ ) to the SUSY Lagrangian [4,5], where  $i$ ,  $j$  and  $k$  are the generation indices. These couplings allow  $B$  or  $L$  violating interactions and, if  $\lambda'_{33k}$  or  $\epsilon_3$  is non-zero, a  $\tilde{t}_1$  may decay directly to SM final states which are experimentally observable.

At the Fermilab Tevatron, in  $p\bar{p}$  collisions, stop pairs might be produced strongly via  $R_p$ -conserving processes through  $gg$  fusion and  $q\bar{q}$  annihilation. In  $\mathcal{R}_p$  scenarios each stop can decay into a tau ( $\tau$ ) lepton and a bottom ( $b$ ) quark with a branching ratio, Br, which depends on the coupling constants of the particular model. A good final state search topology identifies either an electron or a muon ( $\ell = e$  or  $\mu$ ) from the  $\tau \rightarrow \ell\nu_\ell\nu_\tau$  decay, as well as a hadronically decaying tau ( $\tau_h$ ) lepton, and two or more jets.

We present the results of a search for  $\tilde{t}_1\bar{\tilde{t}}_1 \rightarrow \ell\tau_h jj$  events, in the framework of  $\mathcal{R}_p$ -MSSM, using  $106 \text{ pb}^{-1}$  of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8 \text{ TeV}$  collected by the Collider Detector at Fermilab (CDF) during the 1992–95 run of the Tevatron (Run I). CDF is a general purpose detector and has been described in detail elsewhere [6,7]. We briefly describe the

subsystems of the CDF detector relevant to this analysis. The location of the  $p\bar{p}$  collision event vertex ( $z_{vtx}$ ) is measured along the beam direction [8] with a time projection chamber. The transverse momentum ( $p_T$ ) of charged particles is measured in the region  $|\eta| < 1.0$  by a central tracking chamber (CTC) which is immersed in a uniform 1.4 T solenoidal magnetic field [8]. Electromagnetic (EM) and hadronic (HAD) calorimeters, segmented in a projective tower geometry surrounding the solenoid and covering the region  $|\eta| < 4.2$ , are used for identification of electrons, taus, and jets and the measurement of the missing transverse energy ( $\cancel{E}_T$ ). The central strip chamber (CES) is embedded in the central EM calorimeter at a depth of approximately shower maximum, and is used for further electron identification as well as  $\pi^0 \rightarrow \gamma\gamma$  identification from  $\tau_h$  decays. A muon subsystem is located outside the hadron calorimeter and has trigger coverage for the region  $|\eta| < 0.6$ .

The analysis begins with a sample of events which pass a three-level trigger system [6] which requires a single isolated lepton ( $e$  or  $\mu$ ) with  $p_T > 8$  GeV/ $c$  ( $|\eta| < 1.0$  if it is an electron and  $|\eta| < 0.6$  if it is a muon) [9]. Offline, the lepton is required to have  $p_T > 10$  GeV/ $c$ , come from the event vertex, and pass more restrictive identification and isolation requirements [7,10]. An event is removed as a  $Z$  boson candidate if it contains a second, loosely identified same-flavor opposite-sign lepton with  $76 < M_{\ell\ell} < 106$  GeV/ $c^2$ . To maintain the projective geometry of the calorimeter, all events are required to have  $|z_{vtx}| \leq 60$  cm.

An inclusive  $\ell\tau_h$  subsample is made by requiring each event to further contain a high  $p_T$ , isolated, hadronically decaying  $\tau$  lepton candidate with  $p_T^{\tau_h} > 15$  GeV/ $c$  [11] and  $|\eta| < 1.0$ . A  $\tau_h$  candidate is identified as a calorimeter cluster which satisfies the following requirements [12]: (i) not identified as an  $e$  or  $\mu$ ; (ii) one or three tracks with  $p_T > 1$  GeV/ $c$  in a  $10^\circ$  cone around the calorimeter cluster center; (iii) the scalar sum of the  $p_T$  of all tracks in  $\Delta R = 0.4$  around the cluster center, excluding those in the  $10^\circ$  cone, less than 1 GeV/ $c$ ; (iv) fewer than three  $\pi^0 \rightarrow \gamma\gamma$  candidates identified in the CES; (v) more than 4 GeV of  $E_T$  measured in the calorimeter; (vi)  $0.5 < E_T/p_T^{\tau_h} < 2.0$  (1.5) for one track (three tracks); (vii) the cluster width of the calorimeter cluster in  $\eta$ - $\phi$  space less than



0.11 (0.13)  $- 0.025$  (0.034)  $\times E_T$  [GeV]/100 for one track (three tracks); and (viii) the invariant mass reconstructed from tracks and  $\pi^0$ 's less than 1.8 GeV/ $c^2$ . The charge of the  $\tau_h$  object is defined as the sum of the track charges, and is required to have unit magnitude and have the opposite sign (OS) of the  $\ell$  candidate. A total of 642 events pass the above requirements; 16 of these have two or more jets (identified using a fixed cone algorithm with  $\Delta R = 0.4$  [13]) with  $E_T > 15$  GeV and  $|\eta| < 2.4$ . Note that, as expected, the four  $\ell\tau_h$ +jets candidate events which were found in the search for  $t\bar{t} \rightarrow (W^+b)(W^-\bar{b})$  [12] pass the kinematic requirements for this search.

The dominant backgrounds come from  $Z/\gamma^*(\rightarrow \tau^+\tau^-)$ +jets,  $t\bar{t}$ , diboson ( $W^+W^-$ ,  $W^\pm Z$ ,  $ZZ$ ) production, and fake  $\ell\tau_h$  combinations from  $W$ +jets and QCD events. Monte Carlo (MC) programs with CTEQ4L parton distribution functions (PDFs) [14] and a detector simulation are used to estimate the background rates by simulating the kinematics of  $Z/\gamma^*$ ,  $W$ ,  $t\bar{t}$ , and diboson events. All SM processes except  $W/Z$ +jets events are generated using ISAJET [15]; VECBOS [16] is used for vector boson plus jets production and decay, followed by HERWIG [17] for the fragmentation and hadronization of the quarks and gluons. The cross sections for  $Z/\gamma^*$ ,  $t\bar{t}$  and  $W^+W^-$  production are normalized to the CDF measurements [18–21] and next-to-leading order (NLO) calculations for  $W^\pm Z$  and  $ZZ$  production are used [22,23]. The number of fake events from QCD is estimated from the data and assumes that the number of OS events, after subtracting off the non-fake contribution, is identical to the number of like-sign (LS) events observed in the data as expected from QCD sources i.e.,  $N_{QCD}^{OS} = N_{data}^{LS} - N_{MC}^{LS}$ .

The final optimized data selection requirements are based on simulated  $\tilde{t}_1\bar{\tilde{t}}_1$  production, using ISAJET [15] and the CDF detector simulation, background expectations, and a control sample. See Fig. 2. To reduce the number of  $W$ +jets events we require  $M_T(\ell, \cancel{E}_T) < 35$  GeV/ $c^2$  where  $M_T(\ell, \cancel{E}_T)$  is the transverse mass of the  $\ell$  and the event  $\cancel{E}_T$ , defined as  $M_T(\ell, \cancel{E}_T) \equiv \sqrt{2 p_T^\ell \cancel{E}_T (1 - \cos \phi_{\ell\cancel{E}_T})}$ , and where  $\phi_{\ell\cancel{E}_T}$  is the azimuthal angle difference between the  $\ell$  and the  $\cancel{E}_T$ . To reduce the QCD backgrounds we require  $\Sigma p_T(\ell, \tau_h, \cancel{E}_T) \equiv p_T^\ell + p_T^{\tau_h} + \cancel{E}_T > 75$  GeV/ $c$ . A control sample of  $\ell\tau_h$ +0 jet events with similar kinematic

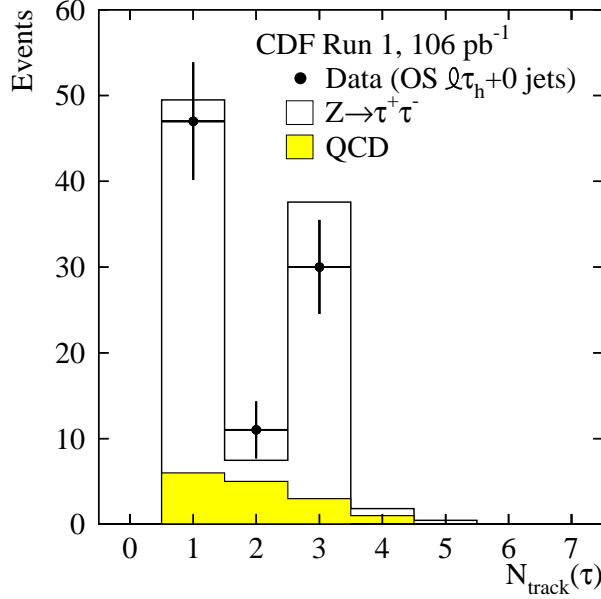


FIG. 1. The number of charged tracks in each  $\tau_h$  candidate for the opposite-sign (OS)  $\ell\tau_h+0$  jet control sample. The data are compared to the MC expectation (all background histograms are summed) which is dominated by real  $\tau_h$ 's from  $Z \rightarrow \tau^+\tau^-$  production.

requirements ( $M_T(\ell, \cancel{E}_T) < 25 \text{ GeV}/c^2$ ,  $|\vec{p}_T^\ell + \vec{\cancel{E}}_T| > 25 \text{ GeV}/c$ ) is selected to show that the backgrounds are well modeled, dominated by real  $Z \rightarrow \tau^+\tau^-$  production, and for later use in the acceptance calculations. Figure 1 shows the charged track multiplicity of the hadronic tau decays (removing the 1 and 3-prong requirements) for this sample and shows good agreement with background expectations.

A comparison of the OS  $\ell\tau_h + \geq 2$  jet data and background estimation is shown in Fig. 2 before the final  $M_T(\ell, \cancel{E}_T)$  and  $\Sigma p_T(\ell, \tau_h, \cancel{E}_T)$  cuts. A breakdown of the backgrounds and data is given in Table I. The backgrounds appear well modeled. A total of  $3.2_{-0.3}^{+1.4}$  events are predicted from all SM sources, dominated by  $Z(\rightarrow \tau^+\tau^-)+\text{jets}$  production. No candidate events pass the final  $\tilde{t}_1\tilde{t}_1$  selection criteria, which is unusual but expected in roughly 3% of experiments when taking into account the statistical and systematic uncertainties.

In order to set limits on  $\tilde{t}_1\tilde{t}_1$  production and decay, the acceptances and efficiencies are normalized to the rate of  $Z(\rightarrow \tau^+\tau^-)+0$  jet decays using the following relation:

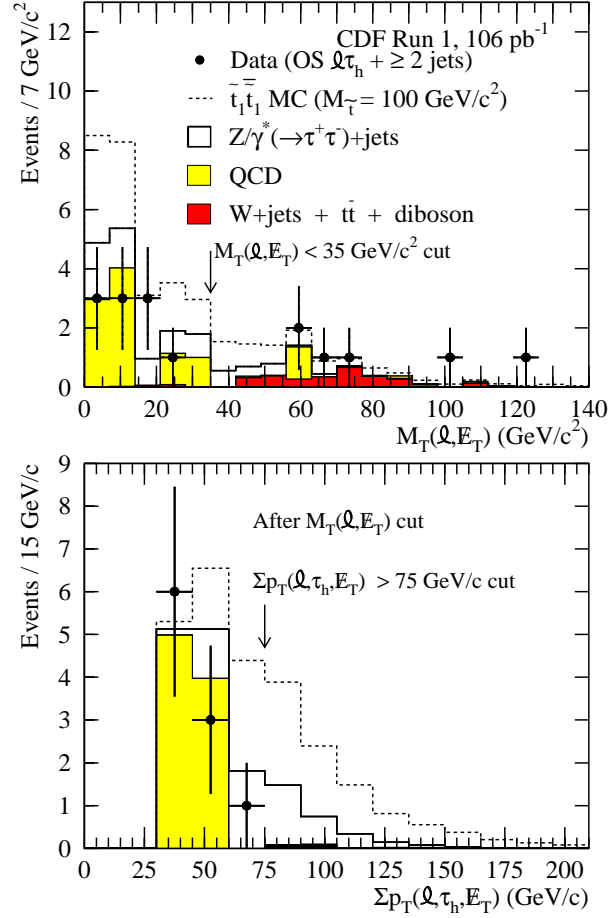


FIG. 2. The final data selection criteria for the OS  $\ell\tau_h + \geq 2$  jet sample. The arrows show the final event selection requirements. The assumed stop mass is  $100 \text{ GeV}/c^2$ . The quantities  $\Sigma p_T(\ell, \tau_h, \cancel{E}_T)$  and  $M_T(\ell, \cancel{E}_T)$  are defined in the text.

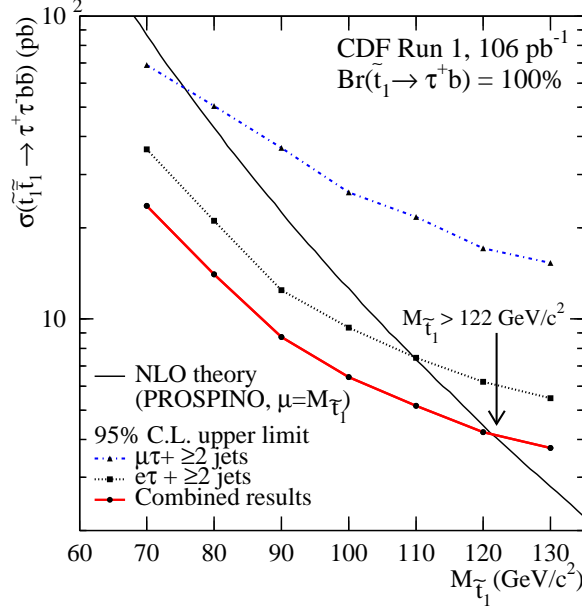


FIG. 3. The 95% C.L. upper limit on cross section for  $\tilde{t}_1\tilde{t}_1$  production compared to the NLO calculations

$$\sigma(\tilde{t}_1\tilde{t}_1 \rightarrow \tau^+\tau^-b\bar{b}) = \left( \frac{N_{\text{stop}}^{\text{Obs}} - N_{\text{stop}}^{\text{BG}}}{N_Z^{\text{Obs}} - N_Z^{\text{BG}}} \right) \cdot R_{\text{Acc}} \cdot R_{\text{Trig}} \cdot \sigma_Z \cdot \text{Br}(Z \rightarrow \tau^+\tau^-) \quad (1)$$

where  $N_{\text{stop}}^{\text{Obs}}$  and  $N_{\text{stop}}^{\text{BG}}$  ( $N_Z^{\text{Obs}}$  and  $N_Z^{\text{BG}}$ ) are the number of candidate events observed in the data and expected background in the  $\geq 2$  jet/ $\tilde{t}_1\tilde{t}_1$  (0 jet/ $Z$ ) selections,  $R_{\text{Acc}}$  is the ratio of the  $Z$  to  $\tilde{t}_1\tilde{t}_1$  acceptances and  $R_{\text{Trig}}$  is the ratio of the trigger efficiencies. The primary advantage of this approach is that potential systematic uncertainties in the estimate of identification and isolation efficiencies are reduced in the ratio of  $\tilde{t}_1\tilde{t}_1$  to  $Z$  production.

The 95% confidence level (C.L.) limits on  $\sigma(\tilde{t}_1\tilde{t}_1 \rightarrow \tau^+\tau^-b\bar{b})$  in the  $e$ ,  $\mu$  and combined channels are found using Eq. (1) and come from a Bayesian integration of the likelihood as

a function of the cross section, integrating over the correlated and uncorrelated systematic uncertainties on the expected signal with a flat prior. The  $R_{Acc}$  term is a function of the  $\tilde{t}_1$  mass and varies in the range  $0.34 < R_{Acc}^e < 2.15$  ( $0.35 < R_{Acc}^\mu < 1.87$ ) for the  $e$  ( $\mu$ ) channel over the range  $70 < m_{\tilde{t}_1} < 130$  GeV/ $c^2$ . The  $R_{Trig}$  term varies between  $0.95 < R_{Trig}^e < 0.97$  ( $0.99 < R_{Trig}^\mu < 1.00$ ) for the  $e$  ( $\mu$ ) channel with an uncertainty of about 1%. (The acceptance and trigger efficiencies for the  $Z$  control sample for this analysis are 1.19% (0.69%) and 74.5% (83.0%) for the  $e$  ( $\mu$ ) channel respectively.) Assuming lepton universality gives  $\sigma_Z \cdot \text{Br}(Z \rightarrow \tau^+\tau^-) = \sigma_Z \cdot \text{Br}(Z \rightarrow \ell^+\ell^-) = 231 \pm 12$  (stat+sys) pb [24]. The dominant uncertainty is due to the statistical uncertainty in  $N_Z^{Obs} - N_Z^{BG}$  and is 17.0% (24.9%) [25]. Additional uncertainty comes from our estimation of  $R_{Acc}$  which is dominated by the variation in the  $\tilde{t}_1\bar{\tilde{t}}_1$  acceptance from choices of the QCD renormalization scale  $Q^2$ , PDFs, amount of gluon radiation, the jet energy scale and the statistical uncertainty in the MC samples [26]. The total uncorrelated uncertainties vary between 17.1 and 17.7% (25.1% and 25.4%), and the total correlated uncertainties vary between 9.3 and 14.1%.

Figure 3 shows the final 95% C.L. upper limits on the cross section times Br for the  $e$ ,  $\mu$  and combined channels, along with the NLO prediction of the production cross sections [27]. The 95% C.L. lower limits on  $M_{\tilde{t}_1}$  are 110 and 75 GeV/ $c^2$  for the  $e$  and  $\mu$  channels, respectively, where we have assumed  $\text{Br} = 1$  for simplicity. Combining the two results yields a limit of 122 GeV/ $c^2$ . Since our analysis does not distinguish the quark flavors in jet reconstruction, these results are equally valid for any  $\lambda'_{33k}$  coupling. These results substantially improve on the currently most stringent mass limit which comes from the ALEPH experiment [28] which excludes  $\tilde{t}_1$  masses below 93 GeV/ $c^2$  using  $e^+e^- \rightarrow \tilde{t}_1\bar{\tilde{t}}_1 \rightarrow \tau^+\tau^- + 2$  jets topology with an assumption of  $\lambda'_{33k} \neq 0$  ( $k = 1, 2$  or  $3$ ).

In conclusion, we have searched for  $\tilde{t}_1\bar{\tilde{t}}_1$  production using 106 pb $^{-1}$  data in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV. We have examined the  $\ell\tau_h + \geq 2$  jet final state within an  $\mathcal{R}_p$  SUSY scenario in which each  $\tilde{t}_1$  decays to a  $\tau$  lepton and a  $b$  quark via non-zero  $\lambda'_{333}$  or  $\epsilon_3$  couplings. No  $\tilde{t}_1\bar{\tilde{t}}_1$  event candidates pass our selection criteria and we have set a 95% C.L. lower limit on the  $\tilde{t}_1$  mass at 122 GeV/ $c^2$  for  $\text{Br} = 1$ .

Sample	$t\bar{t}$	Diboson	$W + \text{jets}$	$Z/\gamma^* \rightarrow \tau^+\tau^-$	QCD	Tot	N <sub>Obs</sub>
OS $\ell\tau$	$1.2\pm 0.3$	$2.3\pm 0.8$	$101\pm 6$	$225\pm 9$	$301\pm 18$	$631\pm 21$	642
$\ell\tau_h + \geq 2 \text{ jets}$	$1.0\pm 0.2$	$0.4\pm 0.1$	$3.4\pm 0.4$	$7.7\pm 0.5$	$8\pm 3$	$21\pm 3$	16
$M_T(\ell, \cancel{E}_T) < 35 \text{ GeV}/c^2$	$0.15\pm 0.07$	$0.14\pm 0.06$	$0.5\pm 0.2$	$6.0\pm 0.4$	$8\pm 3$	$15\pm 3$	10
$\Sigma p_T(\ell, \tau_h, \cancel{E}_T) > 75 \text{ GeV}/c$	$0.15\pm 0.07$	$0.08\pm 0.03$	$0.2\pm 0.1$	$2.8\pm 0.3$	$0_{-0}^{+1.4}$	$3.2_{-0.3}^{+1.4}$	0

TABLE I. Summary of the number of OS events in the data and expectations for the background sources as each selection requirement is applied.

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